STELLAR LUMINOSITIES

By Heber D. Curtis

The *apparent* luminosities of the stars as we see them in the sky or observe them in a telescope are, as is well known, classified in a series of steps known as a magnitude scale, which has been conventionally so formed that a difference of five magnitudes indicates a difference in apparent brightness of just one-hundred-fold. To find the difference in brightness between any given star magnitude and the one next above or next below it, we must take the fifth root of one hundred, which is 2.512. A star of the sixth apparent magnitude is thus 2.51 times fainter than one of the fifth magnitude, 6.31 times fainter than one of the fourth, 15.85 times fainter than one of the third, 39.81 times fainter than one of the second, and just one hundred times fainter than a standard first magnitude star.

But these apparent magnitudes of the stars, useful as they are in certain fields of stellar statistics, are misleading and incorrect as a criterion of the actual relative luminosity of the stars. We know, for example, that there are numerous stars which, though actually giving out much more light than *Sirius,* appear faint to us because they are very much farther away than *Sirius.* Others, though giving out comparatively little light, appear moderately bright because they are close to us.

Could we put all the stars *at the same distance from us,* we should be able to classify the stars with regard to their *actual,* rather than their *apparent,* luminosity. Such a process is, of course, not possible, but if we know how far away a star is from us we can easily find out what its brightness would be were it moved closer to us or farther away so as to be at some arbitrary fixed distance. By common consent among astronomers, this fixed distance has been set at 32.6 light-years[1] (corresponding to a parallax of $0''.1$), and when we have determined how bright a star would be at this distance of 32.6 light-years, we have found what we may term its real relative luminosity, or *absolute magnitude.*

Once we know the parallax (and hence the distance) of a

[1]The light-year is nearly six trillion (6,000,000,000,000) miles.

star, all that we need to determine its *absolute* magnitude is a knowledge of its *apparent* magnitude, and either of two very simple equations which involve only the use of arithmetic and a two-place logarithm table. These equations are:

Abs. Magn. = *App. Magn.* + 5 + 5 × *(logarithm of the parallax in seconds of arc),*

or

Abs. Magn. = *App. Magn.* + 7.6 — 5 × *(logarithm of the distance in light-years.)*

A few examples will serve to illustrate the use of these equations.

What is the absolute magnitude of a star of the eighth apparent magnitude, whose parallax is known to be $0''.045$?

Log .045 = 8.65 — 10, or —1.35, and five times this = — 6.75; whence

Abs. Magn. = 8 + 5 — 6.75 = +6.25.

If a star of the sixth apparent magnitude is as far away as 100 light-years, what must be its absolute magnitude?

5 × log 100 = 10, hence,

Abs. Magn. = 6 + 7.6 — 10 = +3.6.

If a star of the sixteenth apparent magnitude is known to be of the same brightness as our Sun (absolute magnitude + 5), how far away must it be? Here we have,

+ 5 = 16 + 7.6 — 5 × *log distance.*
5 × *log distance* = 18.6, or *log distance* = 3.72, whence,—
Distance = 3,500 light-years.

How bright would our Sun appear (absolute magnitude + 5), if it were moved away to a distance of 10,000 light-years?

+ 5 = *App. Magn.* + 7.6 — (5 × 4.0), and
Sun's apparent magnitude = 17.4

It is now about eight years since Dr. Russell, by plotting the absolute magnitudes of the stars for which data were then available, showed the remarkable progression of absolute magnitude with spectral type, and the clear division of the redder stars into "giants" and "dwarfs." An amount of material is now available which is at least ten times greater as regards quantity and much better as to quality; it will accordingly not be without interest to collect in a single diagram all material at present available.

In a card catalog of all parallax results there are about 5,000 separate entries; many of these, however, are the older results or those secured by methods of inferior accuracy. We have at present (January, 1922) about 1,600 strictly modern photographically determined parallaxes; as there has been, wisely,

considerable duplication, these are distributed among some 1,100 stars.

We have in addition the fine list of 1,646 absolute magnitudes determined by Adams and his associates. By the study of the relative intensities of certain sets of lines in stars of known distances, Dr. Adams concluded that the variations which he found could be used as criteria of the absolute magnitudes of the stars; this then is a method which gives us a parallax determined spectroscopically through the absolute magnitude. Though depending fundamentally on direct parallax results for its scale, it can be applied to stars which are difficult if not impossible to investigate by the direct photographic method of determining parallax. To the above material may be added the list of 556 hypothetical parallaxes of double stars determined by Jackson and Furner.

In pruning our list of directly determined parallaxes and selecting the results to be included there is manifestly abundant room for the exercise of the personal bias of the compiler, and doubtless no two workers in this field would agree precisely as to the material to be eliminated, or as to the method of combination and weighting to be adopted.

In preparing this plot of stellar absolute magnitudes (facing page 33) my effort has been to include only the most trustworthy material, and to leave the more uncertain points for the future to decide. The following principles have governed the method of selection and combination; while in some respects the procedure may have been ultra-conservative, I am aware that it may savor of radicalism in others. I feel certain, however, that we may modify this procedure in any manner within reason, and still obtain a diagram of absolute magnitudes essentially the same as the one shown in this paper.

1. The spectrographic results of Adams, and the hypothetical parallaxes of Jackson and Furner, have been incorporated without change.

2. The direct parallaxes employed are almost without exception strictly modern photographic determinations, though a few heliometer results greater than 0″.050 have been included. No meridian circle parallaxes have been used, nor any values secured through "mass determinations" of parallax.

3. As our direct parallaxes are referred to fainter comparison stars, giving parallaxes relative to these comparison stars, to obtain absolute parallaxes we must increase the values found by the probable parallax of the comparison stars employed. To make this reduction from relative to absolute parallax, 0″.003 has been added to the Mount Wilson direct

results, and 0".007 to the results from all other observatories. The use of a smaller constant than this would make very little difference in the general appearance of the diagram.

4. No negative parallaxes have been used in any case in the formation of mean values, even when the addition of the reduction from relative to absolute would have given a small positive value.

5. To the sources mentioned above there have been added about fifty hypothetical parallaxes secured from members of moving clusters and other methods.

6. No systematic corrections, other than the reduction from relative to absolute mentioned above, have been applied, and all results, by whatever method, have been combined with unit weight.

7. No Cepheids have been included.

8. The spectral type generally follows the Henry Draper Catalog, or Adams when this is not available. Occasionally, in the more crowded portions of the diagram, it has been necessary to place the signs between the Draper and the Adams classifications.

The absolute magnitudes of 2,375 stars, determined in this manner, are shown in the plot, where the vertical coordinates are absolute magnitudes, and the horizontal are the spectral types from the blue B stars through types A, F, G (solar type stars), K, and the redder M type stars. The smaller circles represent the hypothetical results for double stars, the small dots the values secured from direct parallaxes, while the larger circles indicate the spectrographic results of Adams. Where a direct parallax has been combined with a spectrographic or hypothetical value, or both, the resulting absolute magnitude is indicated by the larger solid dots; many of these, representing the mean of three or four modern photographic determinations plus a spectrographic or hypothetical value, may be regarded as very accurately known.

It will be seen at once from this diagram that Russell's progression of absolute magnitude with spectral type is indicated with remarkable clearness along the "dwarf" branch, and also the sharp division of the later spectral types into giants roughly forty times as bright as the Sun, and dwarfs from ten to one hundred times fainter than the Sun (our Sun is of absolute magnitude + 5 and spectral type about G6, an entirely representative member of its stellar class). The bifurcation into dwarfs and giants appears to start rather suddenly at about spectral type G5; before this point the evidence for such a division is none too certain.

From types A0 to about G3 the general "dispersion" in the values is, on the whole, astonishingly small, and some part of the small amount of scattering exhibited may be due to the

inaccuracy of our results. With perfect values of the distances of these stars, it might well be that this portion of the diagram would be even more compact and regular than it is at present. As it is, within these spectral limits, if we can classify an unknown star accurately as to its spectral type, and know its apparent magnitude, we can assign its parallax from these facts alone through an inspection of the diagram about as accurately as we can determine it directly. For example, a star of visual magnitude 9.5, if known to be of spectral type F8, is almost certainty possessed of a parallax of $0''.008 \mp 0''.004$; the probabilities that this parallax of $0''.008$ is in error by more than the amount given are very remote, though there is, of course, the chance that we may be dealing with one of the relatively few giants of the type.

For a star of spectral type K0 the matter is not so simple, and will not be simple till we have more accurate knowledge as to the relative numbers of the giants and dwarfs of this type. The probabilities in this case are that a K0 star of visual magnitude 9.5 has a parallax of either $0''.002$ or $0''.025$. If, as most investigators hold, the dwarfs very greatly outnumber the giants, the chances favor the latter value, and the uncertainty can be removed by determining whether the spectrum is of giant or dwarf type.

The agreement between the values secured by the different methods is very close, on the whole. As the larger dots are used to indicate combinations of direct with the spectrographic or the hypothetical results, this procedure naturally has some effect in "smoothing out" the diagram, yet there remain sufficient individual results by the three methods to emphasize the essential agreement of the data which have been employed in plotting the absolute magnitudes of these 2,375 stars. The omission of all negative parallaxes in forming means, the use of only the larger heliometer values, and the employment of a reduction from relative to absolute parallax larger than has been the custom, all have a tendency to depress the plot in the direction of the fainter absolute magnitudes. But, as in the great majority of the cases just mentioned there exist values by other methods, this effect is believed to be very slight, and the essential agreement of the

results by the different methods with one another and with the combination values supports this view.

One is particularly impressed by the agreement of the hypothetical results for double stars with the rest of the data, as one works through a card catalog of parallax results. These values, from the nature of the case, form the greater portion of the evidence in the types from B8 to F0, and are much fewer among the later spectral types. More interesting, perhaps, than the agreement of these hypothetical parallaxes with the data as a whole, is the confirmation of the hypothesis used in securing these values, namely, that the combined mass of the components of an average double star must be very closely twice the mass of the Sun. This is a further proof, if such were needed, of the essentially average character of our Sun among the stars in general.

From this diagram, also, it is not difficult to see why we get occasional negative parallaxes in the most refined modern work. The visual magnitude of the comparison stars used in most modern direct determinations is from 9.0 to 9.5. From type A0 to G2 our diagram is *perhaps* fairly closely representative of these types; in the later types we feel certain that there are a great number of dwarfs yet to be included. Reasoning from actually existing evidence as shown by the diagram we may then say that the probabilities rather favor a star of visual magnitude 9.5 having parallaxes as follows, according to its spectral type:

Type	Parallax
A5	″.003
F5	.006
G0	.010
K0	.020 (or .002)
K5	.030 (or .002)

The occurrence of even one later type dwarf in a group of three or four comparison stars would certainly make for a small or negative parallax in any distant star under investigation. The determination of the spectral types actually employed in a considerable number of representative fields would go far toward clearing up the question of the magnitude of the correction to reduce from relative to absolute parallax.

Such a diagram forms as well a concrete method of taking stock as to present progress and future needs in the determina-

tion of stellar distances. More direct parallaxes are urgently needed for stars of type A, and for stars of type B our knowledge, as far as direct parallax determinations are concerned, is practically zero. Does the slope of the progression in absolute magnitude as one goes toward the earlier types decrease somewhat, as seems slightly indicated for type A in the diagram, giving us B type stars averaging about $+1$ in absolute magnitude, or does it rise without change so as to approach more nearly to absolute magnitude -1 for the B stars? The stars of this type form perhaps the most urgent, as well as the most difficult, field for direct parallax determinations today, particularly as the spectrographic method cannot as yet be applied to them. So far as the very scanty evidence of the diagram is concerned, we should expect that a very considerable number of the 350 B type stars which are brighter than the fifth magnitude will prove to have parallaxes of the order of $0''.020$. So confident do I feel of this that we are putting a number of early B type stars on the program at Allegheny, and the same thing is being done at the Leander McCormick Observatory. We may find numerous disappointments in the way of negative parallaxes but even so, as a Hibernian might put it, negative results will be positive ones, in a sense.

As to the stars of types K and M, it would seem that our parallax programs are now really overloaded with faint stars of these types possessing large proper motions, exceptional objects through this method of selection; and a type of star of which our present knowledge seems reasonably complete, except as to the relative frequency of their occurrence. It would seem to be much more valuable at present to strive for some such aim as the determination of the distances of all stars which are so bright, and whose proper motions, spectral types, and radial velocities are in general so well known as the stars of Boss's *Preliminary General Catalogue.*